

The European Space Agency's LISA Mission Study: Status and Present Results

U A Johann¹, M Ayre³, P F Gath¹, W Holota², P Marenaci², H R Schulte¹, P Weimer¹ and D Weise¹

¹ Astrium Satellites GmbH, 88039 Friedrichshafen, Germany

² Astrium Satellites GmbH, 85521 Ottobrunn, Germany

³ Astrium Satellites Ltd, Stevenage, Hertfordshire SG1 2AS, United Kingdom

Email: Ulrich.johann@astrium.eads.net

Abstract. The European Space Agency is currently pursuing a comprehensive industrial study of the complete LISA mission within a contract awarded to Astrium Satellites GmbH in 2005. The study is in its final phase and has developed a consolidated mission and payload concept. The feasibility and robustness of the mission concept has been confirmed. The mission performance and the resulting technical requirements have been investigated in detail and converted into an optimised technical design for instrument, spacecraft and constellation. Designed mainly in order to cope with the dynamics of the LISA constellation, three suitable instrument architectures have been defined: (1) two independently rotating opto-mechanical/reference sensor assemblies serving the adjacent interferometer arms with stationary laser beam path inside, (2) one fixed opto-mechanical and two reference sensors assembly with telescope in-field pointing of laser beams, (3) one fixed opto-mechanical assembly with telescope in-field pointing of laser beams and one active reference sensor. The final baseline selection will be guided by mission robustness and reliability, technical complexity, cost and engineering budgets.

1. Introduction

The LISA mission aims at detection of gravitational waves excited in space-time by accelerated compact objects either in periodically (e.g. neutron star or black hole binaries) or as transients (e.g. neutron star/black hole mergers). It opens a new radiation window to the universe at a low frequency band not accessible from ground.

LISA (Laser Interferometer Space Antenna), features three satellites in individual earth trailing heliocentric orbits, which are linked by bi-directional monostatic laser interferometry between free-falling inertial reference masses inside the payload [1,2]. The spacecraft are maintaining an equilateral triangular constellation with 5 Million km armlength, slowly rotating around its normal axis, which itself keeps sun oriented at an offset of 30° to the ecliptic plane; figure 1. Due to orbital distortions, the constellation triangle is not perfectly maintained, but the line of sights offset angle is slowly changing during a one year revolution by $60^\circ \pm 0.75^\circ$. This fact has rather drastic effects on the measurement scheme and engineering solutions.

Along the interferometer beams it causes varying Doppler shifts and unequal varying arm lengths and laterally, it causes variable offset angles between adjacent interferometer arms. This “breathing” variation is far beyond the diffraction limited beam width ($2.5\mu\text{rad}$) and hence requires active tracking. Furthermore, as the triangle plane is also changing its orientation continuously, a variable differential offset of the counter-propagating laser beams along each arm requires active differential steering of in and outgoing laser beams [3]. These dynamic effects in the geometry of the constellation dominate the opto-mechanical architecture of the LISA instrument and hence required considerable attention during instrument engineering. Three suitable instrument architectures have been defined: (1) two independently rotating opto-mechanical/reference sensor assemblies serving the adjacent interferometer arms with stationary laser beam path inside, (2) one fixed opto-mechanical and two reference sensors assembly with telescope in-field pointing of laser beams, (3) one fixed opto-mechanical assembly with telescope in-field pointing of laser beams and one active reference sensor. While feasible according to present analyses and engineering, they differ in terms of mission reliability, robustness, engineering budgets and design criticality of various subsystems and assemblies in a rather complex way.

This paper will summarize the present performance results of the LISA mission study, address the instrument engineering challenges related to the effects mentioned above and briefly introduces the present mission and the three candidate instrument architectures.

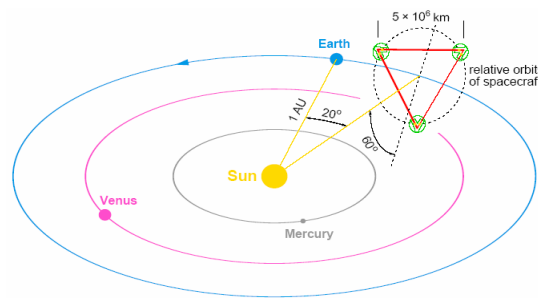


Figure 1. LISA constellation geometry

2. The LISA Mission

The LISA mission is planned as a joined ESA NASA activity with Astrium Germany currently being in charge of an ESA mission formulation study.

The mission duration is planned to 6.5 years with a possible extension to 10 years. The three LISA spacecraft are injected into their individual heliocentric orbits via dedicated, jettisonable, chemical propulsion modules after a Delta 4 or Atlas V launch. The equilateral triangular constellation of three spacecraft, separated by 5 million km from each other and mutually linked by heterodyne laser interferometry in an active transponder scheme, is trailing the earth in their heliocentric orbits at an angular offset of 20° . The triangular plane is revolving over the year, while keeping its normal at 30° tilted with respect to the plane of the ecliptic and pointed towards the sun. The laser interferometers along each arm are referenced to dedicated free falling test masses (cubes) inside the payload. They are kept in their free-fall condition (along the associated laser interferometer axis only and within the desired measurement bandwidth 10^{-5} Hz to 10^{-1} Hz) by a “drag-free” control system, minimizing acceleration distortions from space environment and the surrounding spacecraft itself. The local optics attitude is locked relative to the incoming wavefront planes of the received beams via differential wavefront sensing in the main heterodyne detection chains. The link budget features about 1 W and 100 pW of the 1064 nm laser in the transmitted and received beam, respectively for 400 mm telescope

aperture. Gravitational waves passing the constellation cause pm differential piston/phase modulation of the laser interferometers, detectable by signal processing of all laser heterodyne phase meters which generate beat notes between local and received lasers for all interferometers. The detection sensitivity is constrained in the low frequency band by test mass acceleration noise (e.g. thermo-elastics, electrostatics), in the medium range by laser photon statistics (laser power) and in the high end by antenna (arm length) mismatch.

3. LISA Requirements and Performance Summary

The primary science requirement is the strain sensitivity h of the LISA constellation over the measurement bandwidth as shown in figure 2 for $h/\sqrt{\text{Hz}}$. From an engineering point of view, this has to be broken down to engineering requirements and specifications for instrument elements with balanced apportionment of the tolerable error budget. As seen in figure 3, the low frequency band is dominated by local acceleration noise on the reference masses mainly induced by thermal and charging or magnetic coupling effects, whereas the high frequency band is dominated by optical metrology noise both inside the optical system and between the spacecraft as well as by gravitational antenna size matching. Laser phase noise in the long and unequal interferometer arms by far would dominate the LISA error budget. Therefore a mandatory LISA phase noise compensation scheme - dubbed TDI (Time Delayed Interferometry)[1,2,4]- is applied in post processing by appropriate combination of individual phase measurements in the interferometers spanned by the constellation. It is a prerequisite for LISA to work.

In order to derive from strain sensitivity the engineering requirements on instrument level, i.e. the technical requirements on a single interferometer laser link, the performance of this TDI post processing has to be deducted. From there, the acceleration noise and pathlength noise budget requirements can be established and transferred to technical specifications of each assembly, unit or component.

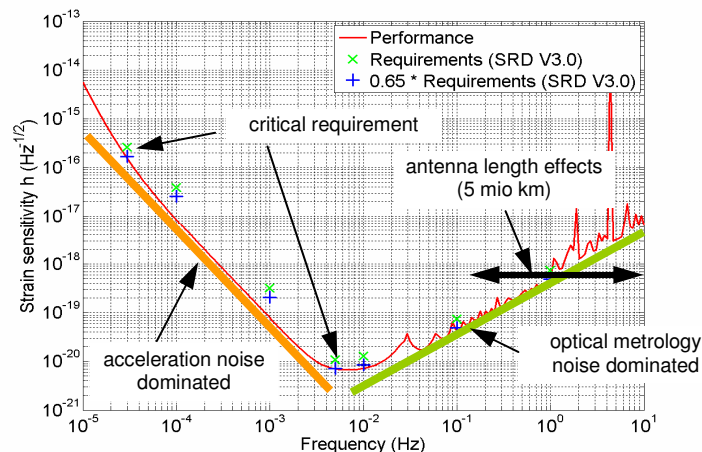


Figure 2. Science requirement and actually simulated performance (curve) for the LISA constellation are plotted in terms of strain sensitivity over the measurement band. The dots indicate specified science requirements (x) and enforced requirements (+).

Figure 3 illustrates the laser frequency noise $/\sqrt{\text{Hz}}$ reduction methodology in three steps. The noise of the free running laser assembly is reduced by active stabilization of the laser e.g. on a reference cavity. Further improvement can be achieved by active locking of the individual phase fluctuations on the various heterodyne sensors, whilst the main part is left to TDI post processing.

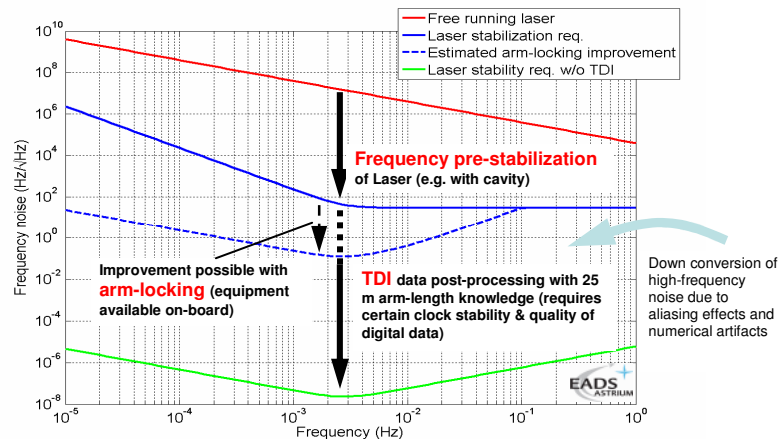


Figure 3. Suppressing laser phase noise as the dominant culprit by a combination of time delayed interferometry (TDI) post processing of heterodyne signals, active laser stabilization and active on-board locking of heterodyne signals in individual arms [5].

The acceleration noise on the reference mass requires the active “drag-free” control of the spacecraft to keep the reference mass along the sensitive axes in free fall. Figure 4 shows the residual acceleration based on a detailed simulation taking into account the environmental and technical distortions. Requirements are met, but marginally at a few 10^{-5} Hz.

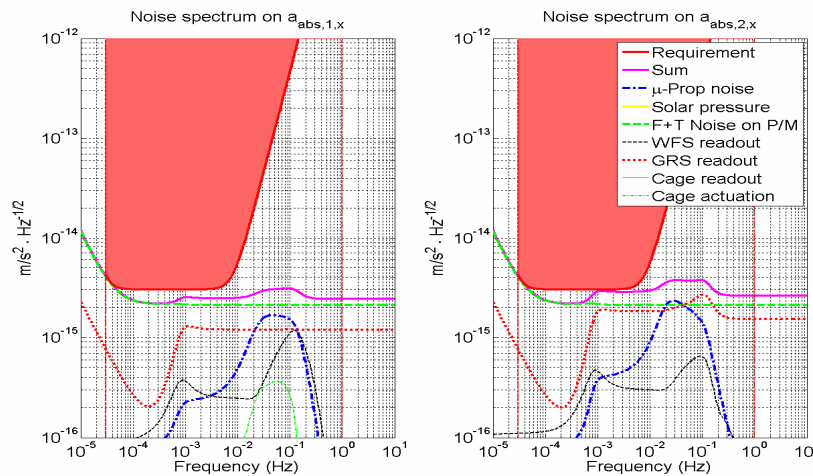


Figure 4. The acceleration noise spectrum is shown for two adjacent interferometer arms in one spacecraft (for instrument architecture (1)), simulated in closed loop with full drag-free control performance and environmental and technical noise included. The total budget (upper curve) is meeting the requirement (shaded excluded area). Individual contributions are shown (thrusters, solar pressure, force and torque on test mass, wave front attitude sensing, test mass read out, optics articulation)

Figure 5 presents the results of a complete performance analysis applied to the single laser link equivalent error expressed in terms of laser phase piston/sqrt(Hz), the quantity finally entering the strain

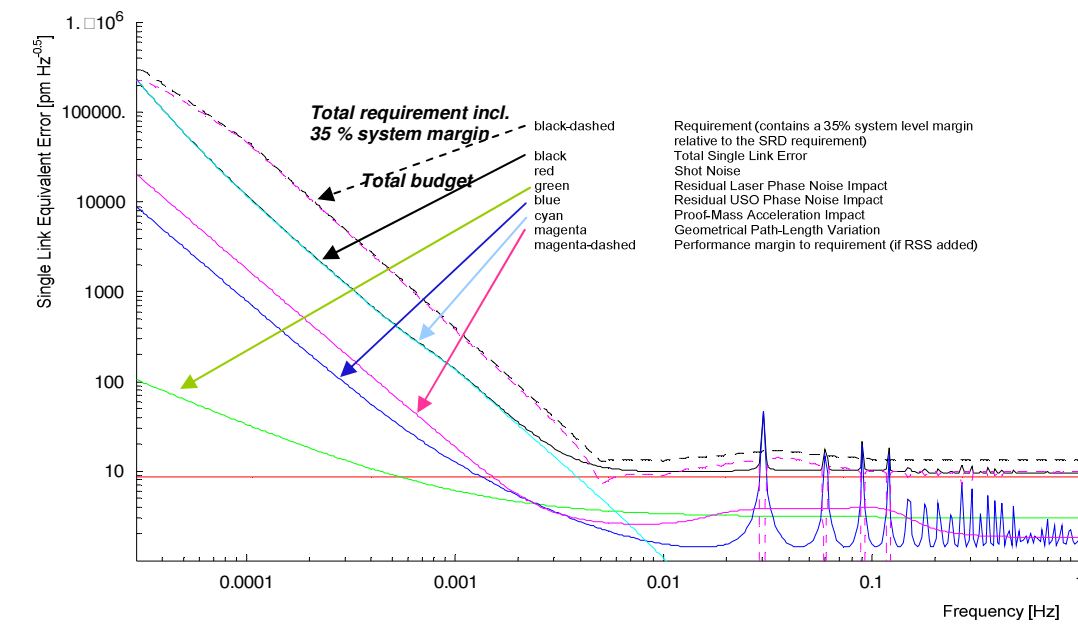


Figure 5. LISA single link equivalent error in terms of laser interferometer piston error based on a detailed simulation taking into account all contributions (for instrument concept (1)). All instrument concepts are similar in performance and meet requirements. Main noise contributors are plotted individually.

determination. The individual residual contributions of the main error sources are plotted and shown to stay in sum in general well below the total requirement even including a 35% system margin to the latter. Exceptions are the residual USO phase noise singularities related to the antenna round trip time.

4. LISA Mission Challenges Driving Payload Architecture

The engineering challenge, in the first place, is the minimisation of technically induced accelerations on the test masses and of laser interferometry phase noise within the measurement band. This translates into demanding, but feasible technical requirements on laser assembly phase noise suppression by on-board measures (active stabilisation and arm locking) and on-ground signal processing (time delayed interferometry) and the control of all technically induced phase effects on the laser modulation and heterodyne phase detection chain. Further, tight requirements are imposed for thermal and thermo-elastic stability in the opto-mechanical chain, comprising telescope and optical bench, as well as on precise test mass relative attitude and position sensing, thruster noise, EMC and self gravity compensation.

For the optics interferometry itself, the main technical challenges to meet the measurement performance can be grouped into four areas:

- Minimize technically induced laser piston/phase fluctuations within the measurement band in both, the transmitted and received beam between local phase references on the optical bench to the system aperture (entrance pupil).
- Provide active transmitted and received beam guidance and pointing stability within the measurement band.
- Minimize cross talk effects from pointing jitter to laser beam phase jitter within the measurement band and caused by geometric projection effects.
- Minimize straylight and polarisation impact on phase detection performance.

The deviation from an ideally, intrinsically stable LISA triangular constellation with equal arms, resting in an inertial frame, leads to following effects:

- Unequal interferometer arm length: laser phase noise dominates phase detection if not compensated for.
- Angular variation within the triangular plane: line of sight lateral offset angle “breathing” around 60° .
- Radial distance variation within the triangular plane: Doppler shift of laser frequency to be accommodated by heterodyne detection.
- In-plane rotation of constellation: fixed offset pointing (nearly) between transmit and received beam.
- Revolution of constellation plane orientation: variable offset pointing between transmit and received beam perpendicular to plane.

The LISA dynamics causes slow relative pointing changes of the adjacent interferometer arms line of sight directions by $60^\circ \pm 0.75^\circ$ for the presently selected orbit parameters as well as Doppler shifts of about ± 20 MHz along the line of sights, both features following a sinusoidal annual pattern. Both figures could be reduced to $60^\circ \pm 0.35^\circ$ and 14 MHz, respectively, by increasing the distance from earth on cost of a more difficult mission operation. As uncovered in the previous study [3], the finite roundtrip time combined with the angular velocity of the line of sight causes an annual sinusoidal varying offset (point ahead) angle of $\pm 6 \mu\text{rad}$ between transmit and received beam and perpendicular to the constellation plane. That value already vastly exceeds the diffraction limited beam divergence of about $2.5 \mu\text{rad}$. The addressed group of effects is requiring dedicated mechanisms to precisely sense and actuate common and differential line of sight directions, respectively, as well as a laser frequency map and beat note down-mixing scheme.

The present Astrium study has uncovered also further geometrical projection effects in the near and far field of the laser beams (at local or remote spacecraft, respectively), causing pointing jitter to piston/phase jitter cross talk within the measurement band not tolerable for the measurement requirements. These geometrical effects appear at various places in the measurement chain and are of high importance for the performance budget [6, 7].

5. Mission Architecture

The LISA mission architecture is based in a launch of a stack of three spacecraft, each comprised of an individual chemical propulsion module and a sciencecraft comprising the instrument [8]. The propulsion modules are shrouding the sciencecraft during launch and transfer orbit from contamination. The total launch mass of the stack is about 4800 kg. The individual masses of the propulsion module and sciencecraft are 272 kg (dry) and 575 kg, respectively. The propulsion module delivers a Δv of 1130 m/s and the sciencecraft power capacity is 890 W. These values vary slightly depending on design optimization and instrument architecture selected.

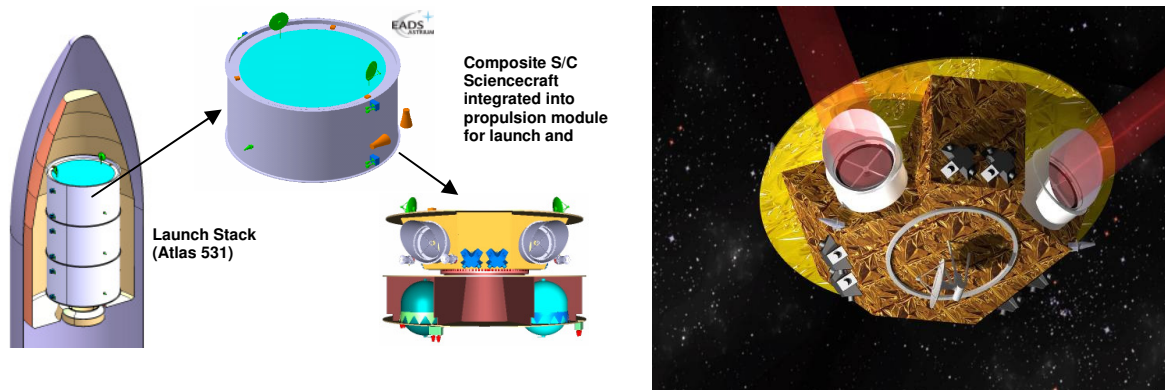


Figure 6. LISA mission architecture. The left part shows the launch stack of three spacecraft under an Atlas V fairing. Each element consists of the dedicated propulsion module, shrouding the sciencecraft during launch and orbit injection. The right part shows the science craft from underneath (kept in shadow). The diameter is about 2.20m.

6. Classical LISA Payload Configuration (1)

The optical payload consists in the configuration as originally proposed [1] of two assemblies, each one comprising a telescope, an optical bench and an inertial sensor and serving one arm of the adjacent interferometers, figure 7 and [8, 9]. While allowing almost stationary on-axis operation of the optics, the arrangement requires two separate active inertial sensors, a challenging launch lock and articulation mechanism, a rather sophisticated optical interfacing between the interferometer arms and active electrostatic suspension of the two test masses in all but one degree of freedom.

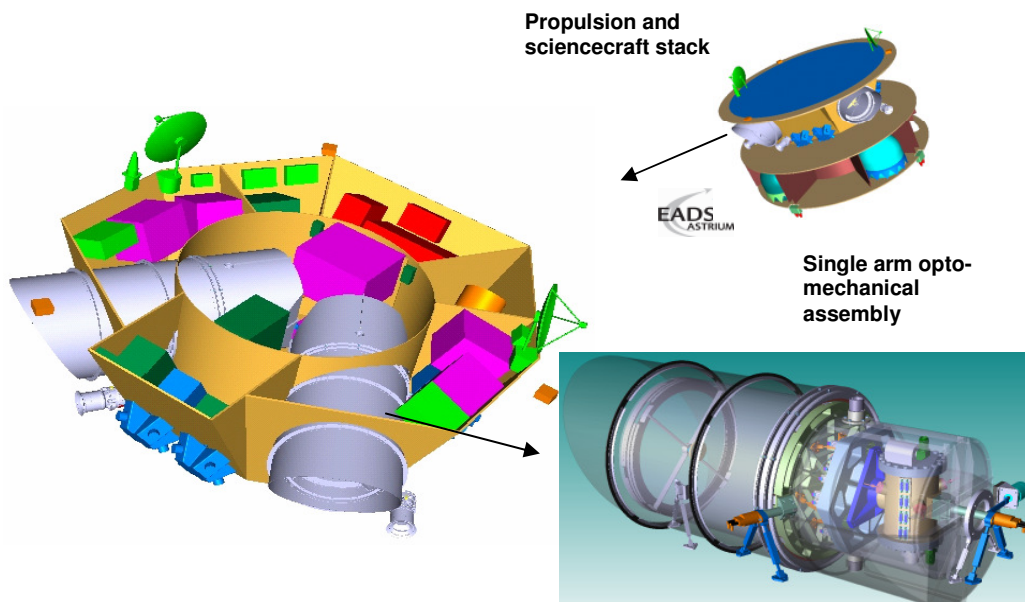


Figure 7. LISA instrument architecture (1). Two complete optical/reference sensor assemblies are accommodated within the science craft, one for each interferometer arm. They can be articulated in the constellation plane wrt. their offset angle. Each assembly (lower left) comprises from left the 400 mm telescope, an interface structural plate, an optical interferometer bench and an inertial reference sensor.

7. Alternative LISA Payload Configuration (2)

To avoid the large opto-mechanical assemblies in the classical architecture (1) with their complex launch lock, articulation needs, and elastic interferometer back side combination, a much more compact configuration with fixed crossed telescopes has been developed, see figure 8. It features a single rigid interferometer optical bench for both arms, two active dedicated inertial sensors and two compact crossed off-axis telescopes. The off-axis feature (also possible in the architecture (1)) avoids critical straylight and narcissus effects. The breathing angle variation is accomplished by an in-field pointing mechanism located at an intermediate pupil plane and operating on both, transmitted and received beam. The inertial sensors test mass centers are located at their respective telescope line of sight center and kept in free fall along that axis.

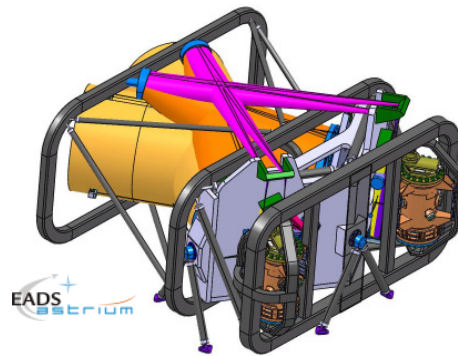


Figure 8. LISA instrument configuration with two active inertial sensors and fixed off-axis telescopes in compact crossed configuration and dedicated to both interferometer arms. The breathing angle actuation is accomplished by in-field pointing of both, transmitted and received beam.

8. Alternative LISA Payload Configuration (3)

A further evolution for the alternative instrument configuration is relying on a single active inertial sensor per spacecraft [6, 7] (here with another one in cold redundancy in proximity at the symmetry line). The off-axis telescopes again are fixed with in-field pointing actuation. The intersection of the telescopes line of sights defines the position of the active inertial sensor center of mass to minimize geometrical pointing to piston cross-talk effects. The test mass is sensed by laser interferometry in two axes within the constellation plane. The redundant sensor should be in close proximity in order to keep the impact of these effects in a range which can be compensated for thanks to precise pointing knowledge from the main heterodyne differential wavefront sensor and in-field actuator jitter sensing.

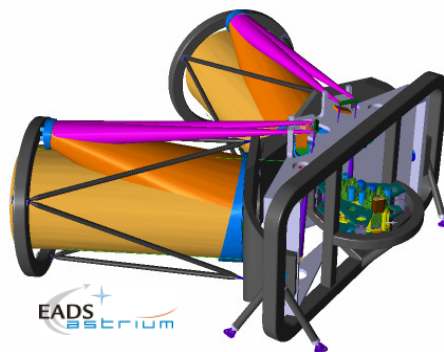


Figure 9. LISA instrument configuration based upon a single active inertial sensor and fixed off-axis telescopes with in-field pointing. This is the only configuration which provides full mission performance with only three inertial sensors operating and at full inertial sensor cold redundancy.

9. Conclusion

ESA's industrial study carried out by Astrium GmbH with Astrium Ltd and TNO in close cooperation with institutes and NASA has advanced well since starting in 2005 and will conclude mid 2008. Detailed performance analyses engineering and design activities have been carried out. No show stoppers have been found and three principal candidate instrument architectures have been developed, which have similar performance. Technical requirements underlining the feasibility have been derived while observing maximum LISA pathfinder heritage.

The instrument architecture (3) featuring for each spacecraft a single active inertial sensor and two rigid telescopes with in-field pointing is most attractive, as providing full performance with only three inertial sensors operating and full cold redundancy for these critical units with none or marginal performance degradation.

10. Acknowledgements

This work was supported in part under ESA Contract No. 18756/04/NL/HB. The authors wish to acknowledge the fruitful collaboration in the LISA study they enjoyed with the ESA, NASA and science teams.

References

- [1] LISA Study Team, 1998, *LISA Pre-Phase A Report, 2nd edition, Report MPQ 233*, Max-Planck-Institut für Quantenoptik (Jul 1998)
- [2] LISA Laser Interferometer Space Antenna, a Cornerstone Mission for the Observation of Gravitational Waves, 2000, *System and Technology Study Report, ESA-SCI_2000_11*, The European Space Agency (July 2000)
- [3] LISA Feasibility Study Final Technical Report, 2000, *ESA Contract No. 13631/99/NL/MS, Report o. LI-RP-DS-009*, Dornier Satellitensysteme GmbH (April 2000)
- [4] Tinto M and S. Durhandhar, Time Delayed Interferometry, 2004, *arXiv.org; gr-qc/0409034*.
- [5] Herz M, Active Laser Frequency Stabilisation and Resolution Enhancement of Interferometers for the Measurement of Gravitational Waves in Space, 2005, *SPIE Optical Engineering, Vol 44(9)* (Sept. 2005)
- [6] Johann U A, Braxmaier C, Holota W, Jörck H, Novel Payload Architectures for LISA, 2006, *Proc. International Conference on Space Optics ICSO*, 27-30.June, ESTEC, Noordwijk, The Netherlands, (27-30.June 2006)
- [7] Johann U A, Gath P F, Holota W, Schulte H R and Weise D, Novel Payload Architectures for LISA, 2006, *Proceedings of the 6th International LISA Symposium*, NASA GSFC, Greenbelt, Maryland, USA (19-23 June 2006)
- [8] Gath P F, Johann U A, Schulte H R, Weise D and Ayre M, 2006, *Proceedings of the 6th International LISA Symposium*, NASA GSFC, Greenbelt, Maryland, USA (19-23 June 2006)
- [9] Weise D, Braxmaier C, Gath P F, Schulte H R and Johann U A, 2006, Optical Metrology Subsystem of the LISA Gravitational Wave Detector, *Proc. International Conference on Space Optics ICSO*, ESTEC, Noordwijk, The Netherlands (27-30.June 2006)